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DEPARTMENT OF DEFENCE
DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION

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ABSTRACT

Available literature on the effects of underwater explosions on life in the sea is reviewed. Reported effects on marine plants, invertebrates, fishes, turtles, birds, sea mammals and humans, from both experimental and field observations, are presented, as are theories on the damage process and models developed to predict lethal and safe ranges around explosions of varying configurations.

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Executive Summary

Underwater explosives are used in a range of commercial and military operations, such as for clearing shipping lanes, seismic investigations, military training exercises, and shock testing new naval vessels. These explosions may have an effect on nearby marine life and incidents have occurred, such as during an RAN exercise in Jervis Bay in 1988, in which large numbers of fish have been killed. As a result, the planning process now invariably requires an assessment of the potential impact on the marine environment of inshore activities involving underwater explosions, including their impact on marine life. For Defence, shock testing new vessels, such as the Bay class minehunters and the Collins class submarines, is a case in point. For such an asssessment relevant information has been widely scattered through the technical literature and this review attempts to bring this information together. Reported effects of underwater explosions on marine plants, invertebrates, fish, turtles, birds and sea mammals are presented, as well as theories on the damage process. Fish and marine mammals have been found to be particularly vulnerable to the effects of underwater explosions and models developed to aid in the prediction of lethal and safe ranges around explosions are included in the review. Safe ranges for humans and secondary effects which may impact marine communities are also discussed.

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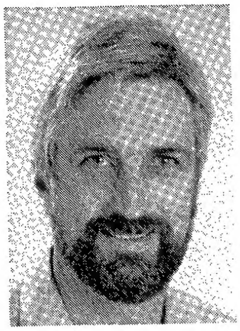

John Lewis graduated from the University of Melbourne with a BSc (Hons) (1975) and an MSc (1977) in marine biology. Since graduating, he has worked at MRL where his primary research interests have been in marine fouling and its prevention and the effects of RAN activities on marine communities. He is presently Task Manager of a Navy sponsored task which primarily addresses the environmental acceptibility of organotin antifouling systems and appraisal of tin-free alternatives.

Contents

1. Introduction

The use of underwater explosives is widespread and the applications are many and varied, including the clearing of obstructions from shipping lanes, underwater demolitions and seismic investigations. For the military, underwater explosives are used in training exercises, mine disposal and underwater demolitions techniques, and for shock testing new vessels.

Increasingly there is a requirement to assess the potential impact of such activities on the marine environment, including their impact on marine life. Relevant information is widely scattered through the technical literature and this review attempts to bring this information together. The effects of underwater explosions on each of the major biological groups within marine communities is addressed, and consideration also given to effects on underwater habitats.

2. Marine Plants

Little information has been published on the effects of underwater explosions on marine plants. Ludwig (1977) monitored the effects of explosions used to clear a channel through dense stands of the seagrass *Zostera marina* in the Niantic estuary in Connecticut, U.S.A. Experimental detonations were performed with single and multiple charges and a weighted length of detonator cord. The immediate impact of a single charge was a small crater 45 cm in diameter and 15-20 cm deep. Over an eight week period following the explosion, the seagrass exhibited orderly dieback to give a cleared area 7-8 m in diameter. Chain detonations created overlapping rings of impact which ultimately cleared a rectangle approximately 40 m long and 7-8 m wide. The detonator cord cleared a rectangle 2-4 m wide. Dieback of the seagrass was attributed to direct disruption of vascular structures within the rhizomes and therefore did not affect the non-vascular benthic algae.

An indirect effect of underwater explosions on benthic vegetation can be caused through disturbance of the bottom sediments. Such disturbance can change the redox potential of the sediment and release toxins; the resuspension of sediment can reduce light penetration and photosynthesis and smother seagrass as it redeposits (Heinsohn *et al.* 1977). Changes in the redox potential can make sediments unfit for seagrass recolonization (Wood 1959).

3. Invertebrates

Aplin (1947) conducted several experiments to determine the effects of underwater explosions on lobsters (*Panuliris interruptus*) and abalone (*Haliotis corrugata, Haliotis fulgens*). In two experiments, lobsters were exposed to 20 lb [9.1 kg] charges detonated 4 ft [1.2 m] below the surface. In the first, 8 lobsters were located on the bottom 55 ft [16.8 m] from, and almost directly below the charge, while in the second 13 animals were caged 4 ft below the surface and 50 ft [15.3 m] from the charge. All the lobsters survived the explosions and when killed their viscera showed no sign of damage. Eight abalone located 55 ft below a 20 lb explosion apparently survived the explosion but died within a few hours when transferred to an aquarium. However, this result was considered inconclusive as the animals may have died as a result of handling and transportation.

In experiments conducted by the Chesapeake Biological Laboratory (Chesapeake Biological Laboratory 1948, O'Keeffe and Young 1984), blue crabs (*Callinectes sapidus*) and American oysters (*Crassostrea virginica*) were held in cages at fixed depths and distances from explosives fired in relatively shallow water. Of 258 oysters located at distances from 20 [6.1] to 700 ft [214 m] from 27-31 lb [12-14 kg] charges, only two were killed: one at 80 ft [24.4 m] and one at 100 ft [30.5 m]. In a second series of tests, only 4 of 184 oysters located within 200 ft [61 m] of a 300 lb [136 kg] charge were killed immediately, but a further 10 subsequently died within 2 weeks. No mortalities were recorded for oysters 400 ft [122 m] from the charge. The study concluded that over a limited area a relatively small percentage of the oysters would be killed by underwater explosions and that many may survive even when quite close to the charge. Increasing the size of the charge did not greatly increase the percentage killed or the lethal radius. Blue crabs were less resistant to the effects of 30 lb [13.6 kg] charges than oysters, with 89% of those held within 25 ft [7.6 m] of the explosions killed. Between 50 [15.3] and 125 ft [38.1 m] of the charges 38 to 55% were killed, whilst at 150 ft [45.8 m] only 7% died.

The effect of larger charges on these species was investigated by Gaspin (1975) and Gaspin *et al.* (1976). In the first tests, animals were caged at distances ranging from 40 [12.2] to 110 ft [33.6 m] from 200 lb [91 kg] charges detonated in 25 ft [7.6 m] of water. Mortality varied from 0 to 58% but no clear trends were evident in the pattern of mortality. Gaspin's only conclusion was that crabs and oysters were highly resistant to underwater explosions. In the second tests, cages were placed at distances of 20, 30, 50, 100, 150 and 200 ft [6.1, 9.2, 15.3, 30.5, 45.8 and 61 m] from a 106 lb [48.1 kg] charge. Blue crab mortality appeared to decrease linearly with increasing distance from the charge, but high mortality of control animals cast doubt on the results. Oysters were only killed in the 20 ft cage. Other invertebrates (sea anemones, polychaetes, isopods and amphipods) observed in the cages were undamaged.

From the above studies, O'Keeffe and Young (1984) concluded that one could safely assume that commercially important benthic life such as clams, oysters, and crabs are highly resistant to shock.

Linton *et al.* (1985) also exposed blue crabs and American oysters, together with white shrimp (*Penaeus setiferus*), in surface and bottom cages at distances of 1 to 136 m from a 33 m strand of detonator cord. The mortality of blue crabs was directly related to distance from the site of detonation, with 40% killed immediately at the 1 m site but only 10% at 46 m. Few additional mortalities were recorded over the subsequent 24 hours. Shrimp died in all test cages and depths but with no well-defined pattern. Mortality varied between 5 and 35%. Only 5% of the oysters died in the 1 and 11 m cages, 15% in the 23 and 46 m cages, and all survived in the 146 m cage.

Kemp (1956) had previously observed that shrimp and crabs were completely immune to 20 kg dynamite charges, whilst oyster mortality varied between 10 and 30%. Damage to the latter was most severe within a 7.5 m radius of the detonation zone. Spears (1980) found that most shrimp and crabs in near-surface and bottom cages within 22.5 m of a primacord explosion were killed. Dunstan and Lewis (1980) observed that, on an intertidal mudflat, crabs adjacent to an exploding detonator cord at low tide were blown out of their burrows but only those in the direct path of the explosive were damaged.

Alcala and Gomez (1987) found few documented reports on the effects of blast fishing on invertebrates in the Philippines, but assumed that those found in the centre of the blast area, whether in coral interspaces or in the water column would be killed outright. In one instance, bivalves outside the rim of a recently blasted area were found dead, and in the longer term dynamite-blasted reefs were found to support fewer bivalve and gastropod species than intact reefs. A bomb the size of a beer or coke bottle, as commonly used in blast fishing, exploding at or near the bottom destroyed all stony corals within 3 m, while a gallon-sized charge would destroy an area 10 m in diameter. The physical damage became progressively smaller as the point of explosion increased in vertical distance from the bottom.

The use of explosives by fishermen, though generally illegal, is widespread in the tropical Indo-West Pacific and some parts of the Caribbean (Alcala and Gomez 1987, Johannes 1975). The extent of the practice is such that it has become a serious cause of coral reef degradation in some areas. For example, in Micronesia blast fishing has been considered the most important human activity causing reef destruction (Tsuda 1981).

4. Fishes

4.1 Fish Kill by Underwater Explosions

Fish have been found to be particularly vulnerable to the effects of underwater explosions and are killed over a much greater range than other organisms. Various studies have documented the fish kill associated with explosions and some of these are summarized in Table 1. However, most of these figures must be considered as conservative as, in most instances, the fish kill was determined by collecting dead fish from the water surface immediately after the explosion. Not all dead fish float and mortally wounded fish which died after the sampling would not be counted. For example, the report on tests conducted by the Chesapeake Biological Laboratory to determine the effects of underwater explosions on marine life in Chesapeake Bay commented that the accumulation of dead fish on the bottom made sampling by oyster dredge difficult (Chesapeake Biological Laboratory 1948) and Yelverton *et al.* (1975) found that killed fish did not consistently rise or sink. Alcala and Gomez (1987) observed that fish killed by blast fishing generally sink to the bottom and are collected by divers individually by hand. Fitch and Young (1948) estimated that 8 to 50% of fish killed would not be visible from the surface.

Young and Willey (1977) proposed techniques for monitoring the effects of explosions on marine life. Post-shot evaluation of fish kill involved the determination of the area of visible kill, surface trawling to collect a representative sample of floating dead fish and bottom trawling to collect dead fish which settle to the bottom. The ratio of volume swept in the trawls to total volume can then be calculated and used to estimate total fish kill. However, these authors note that the occurrence of wind, currents, rough water and irregular bottoms all reduce the reliability of such monitoring procedures.

The anatomical damage found in fish killed by explosives was summarized by Ronquillo (1950) to assist in recognition of blast-killed fish during investigations of suspected instances of blast fishing. The following anatomical effects were listed:

1. The air bladder (or swim bladder), if present, is almost always ruptured and blood clots are found in its lumen.
2. The vertebral column may be fractured in any part along its length.
3. Localized haemorrhages are present around the area of fractured parts due to the destruction of the blood vessels and tearing of adjacent tissues.
4. Parts or all of the contents of the body cavity may be damaged or crushed, with haemorrhages depending upon the size, shape, position and distance of the fish from the explosion.
5. Fracture and/or dislocation of the abdominal ribs from the vertebral column may be found especially in spiny fishes, with accompanying haemorrhages present in the area of the fracture.
6. The blood vessels below the vertebral column may break and cause haemorrhages of varying degrees along that region.
7. Rupture of the parietal peritoneum, especially that attached to the abdominal ribs.

Table 1: Fish kill recorded from underwater explosions.

Source	Weight of Charge (kg)	Depth of Water (m)	Detonation Depth (m)	No. of Shots	No. Killed	Weight Killed (kg)
Aplin (1947)						
60%	4.5	25-28	0.9	1		4
petrogel		"	1.2	4		1 - 10
		18-20	"	4		8 - 34
		11	"	1		454
	9	25-28	"	3		2 - 5
		18 - 20	"	9		8 - 29
		11	"	2		0.5 - 234
		18 - 20	2.4	1		24
		25 - 28	6.1	2		6 - 13
		18	"	1		463
	18	25 - 28	1.2	6		0.5 - 454
		18 - 20	"	5		6 - 30
		11	"	4		5 - 227
		25 - 28	6.1	1		64
Coker & Hollis (1950)						
HBX[2]	114	41	15 - 21	3	121 -4194	41 - 2500
			36 - 41	2	80 - 348	17 - 59
	204	"	21	1	606	111
	272	"	5.2	2	208 - 254	41 - 91
	272 - 291	"	21	6	486 - 6028	98 - 2235
	545	"	21	5	0 - 4004	0 - 657
			34	1	262	79
Hubbs & Rechnitze(1952)						
dynamite	23	18 - 107	18 - 107	10	1431 (total)	
	23 or 46	15 - 27	15 - 27	5	9 - 2134	
	23 or 46	99 - 131	99 - 131	5	12 - 286	
Falk & Lawrence (1973)						
geogel	1.1	2.1	2.1	1	2	
	2.3	4.6	4.6	1	1	
	4.5	4.6	3.1	1	400+	
aquaflex	50.3 m	4.6	4.6	2	2 - 10	
	50.3 m (x2)	4.6	4.6	1	20 - 30	
Young & Willey (1977)						kill range
exp'mental	4.3		4.6	1	small no's	122 m
pentolite	9.1		6.1	1	< 100	107 m
	9.1		3.1	1	31+	98 m
TNT	41		6.1	1	1000	300+ m
baratol	1.1		5	1	50	

The vulnerability of fish to explosions is related to the presence of a swimbladder (Wiley *et al.* 1981), a gas-filled sac which lies in a dorsal position in the visceral cavity, close up against the underside of the vertebral column between the alimentary canal and the kidney (Figure 1). The function of the swimbladder is principally hydrostatic, although many

species also use the swimbladder to generate sound and as an aid in hearing. The gas content in the bladder is varied by the release of oxygen from a concentration of small blood vessels, the so-called "red" gland. This enables the fish to maintain its position in the water column without muscular exertion (de Beer 1951). Bottom living fish, such as flatfish, do not have a swimbladder. Many species also use the swimbladder to generate sound and as an aid in hearing. In swimbladder fish, the swimbladder is roughly elliptical and must occupy about 5-7% of the total body volume in order to effect the proper density control of the fish (Christian 1974).

Aplin (1947) found that, although most fish killed by explosions had ruptured blood vessels and, in some, the contents of the body cavity were crushed and ribs broken, all had ruptured swimbladders. In follow-up experiments with fish suspended in cages at set distances from shots, fish without swimbladders were apparently unhurt by explosions which reduced to pulp the viscera of swimbladder fish held in the same cages. Gaspin (1975) also found fish without swimbladders to be uninjured at positions where swimbladder fish suffered heavy damage. Fish killed by explosions in Chesapeake Bay seldom showed gross external injuries (Coker and Hollis 1950). However, many had distended abdomens and, internally, all fish examined had ruptured swimbladders and some degree of haemorrhaging of the vascular system, liver and spleen. Similarly, Yelverton *et al.* (1975) found the internal organs most commonly damaged by explosions to be the swimbladders, kidneys and livers. In most instances, haemorrhaging was associated with the disruption of these organs, but in no instance was the abdominal wall ruptured. Linton *et al.* (1985) found the swimbladder, kidney and peritoneum to be the most frequently damaged organs in fish caged near an exploding detonator cord. The only visible external injuries were loss of opercular scales. Sakaguchi *et al.* (1976) considered rupture of the sinus venosus to be the major cause of death, although the kidney, liver and swimbladder were also frequently damaged.

Hubbs *et al.* (1960) developed a set of damage criteria which permitted quantitative evaluation of injuries to fish exposed to explosions (Table 2). These criteria have since been used in a number of investigations of explosion effects (Gaspin 1975, 1977, Gaspin *et al.* 1976, Goertner 1978b, Munday *et al.* 1986, Wiley *et al.* 1981, Young and Willey 1977). A damage level of two or higher was considered to constitute lethal damage (Gaspin 1975). Although Gaspin found that few fish which sustained a damage level of two were killed outright, a fish with this degree of damage was considered unlikely to survive as it would be subject to selective predation. However, if kept in a holding tank away from predators, such fish showed a remarkable ability to survive and heal wounds (Gaspin 1977, Gaspin *et al.* 1976).

Table 2. Damage criteria (as cited in Gaspin 1975).

Damage Level	Criteria
(0)	No damage.
(1)	Only light haemorrhaging, principally in the tissues covering the kidney.
(2)	Swimbladder intact, but with light haemorrhaging throughout the body cavity, with some damage to the kidney.
(3)	No external indication of damage, but with the swimbladder usually burst. Haemorrhaging and organ disruption less extreme than in (4) and (5), but with gross damage to the kidney.
(4)	Incomplete break-through of the body wall, but with bleeding about the anus. The swimbladder is almost invariably broken and the other organs damaged as noted under (5).
(5)	Rupture of the body cavity. The break is usually a slit just to the side of the midventral line. Associated with this severe damage is a burst swimbladder and gross damage to other internal organs. The abdominal contents are often completely lost or homogenized

Rasmussen (1967) compared the effects of pressure on newly hatched herring and salmon fry, in which the swimbladder would not have developed, with effects on the same fry after the swimbladder developed. He found that the newly hatched fry were apparently unaffected by pressure change, whereas fry at 3 to 6 months of age died if exposed to pressures exceeding 2.7 psi [18.6 kPa or 205 dB re 1 μPa].

The number of fish killed will depend on the numbers within the lethal zone at the time of detonation, and this accounts for the large variability in the number of fish killed by equal charges detonated at similar depths (Table 1). In open waters, most fish within the water column are migratory and the abundance of fish in a particular area will vary greatly according to local fish movements. Explosions apparently have no deterrent effect on fish and Coker and Hollis (1950) saw no reason to believe that fish were frightened from the area of a blast. Through the series of tests they observed, mortality varied widely and the species composition for the bulk of the fish remained fairly constant. In contrast, Fitch and Young (1948) found that when explosions were repeated within 24 hours at the same location, the species composition of the fish killed was entirely different. An examination of the stomach

contents of the fish killed on the second day revealed them to be feeding on the bodies of fish killed on the first. Areas can be depopulated by repeated blasts, as observed after successive explosions in a submarine canyon, but repopulation of the area did take place within a few months (Hubbs and Rechnitzer 1952). Aplin (1947) observed no deterrent effects to schools of anchovies or tuna feeding within the concussive zone of explosions.

The zone of fish-kill around an underwater explosion is asymmetric with fish near the water surface apparently more vulnerable than fish deeper in the water column. From observations on the effects of explosions in Chesapeake Bay, Coker and Hollis (1950) suggested that only free-swimming fish in the upper strata of the water column at the time of the explosion were killed. Similarly, Tiller and Coker (1955) observed heaviest mortalities in fish which live or feed near the surface or move frequently into the middle or upper parts of the water column. Hubbs and Rechnitzer (1952) found in experiments with dynamite that, while fish in surface cages were physically damaged by a blast, the same species of fish in bottom cages nearest the explosion often suffered no harm or less damage. It was also noted by these authors that the free fish killed were mostly surface rather than bottom inhabitants. This observation could only be explained in part by the absence of swimbladders in many bottom dwellers, as some species with large swimbladders were in the immediate area during some of the tests but few were killed. Further analyses of Hubbs and Rechnitzer's data by Christian (1973) showed that the near- surface fish were killed by lower amplitude pressure waves than the fish near the bottom.

In apparent contrast, Linton *et al.* (1985) found fish caged on the bottom to be more susceptible to the effects of a detonator cord explosion than fish caged near the surface. In their experiments, black drum (*Pogonias cromis*) and red drum (*Sciaenops ocellatus*) were caged near the surface and on the bottom at distances of 1, 11 23, 46 and 136 m from a 33 m long strand of detonation cord (100 g powder/33 cm) lying along the bottom in water 2.4 m deep. Of the ten fish of each species held in each of the surface cages, only one was killed: a black drum in the 1 m cage. However, in the bottom cages, 17 of the 50 black drum were killed immediately and a further 15 died within 24 hours. Swimbladder damage was greatest at sites furthest from the explosion (46 and 136 m). All red drum, except those in bottom cages at the 1 m distance, survived detonation but many had internal injuries. After the explosion, some free- water fish were found floating near the surface well beyond the cages 136 m from the point of detonation. The kill probability contours generated by O'Keeffe (1984) show that a region of "safe" water occurs close to the surface and Linton *et al.*'s surface cages may have been in this region. Injuries to fish close to the detonation cord suggest that these fish were damaged directly by the pressure wave, whereas swimbladder damage to fish further away implicates the rarefaction wave after surface reflection (see below).

Burying charges in the seabed does not prevent fish kill. Rasmussen (1967) reported that when dynamite charges were buried in the seabed, mortalities occurred all the way to the surface with more fish killed near the surface than near the seabed. However, the lethal effect could be reduced by increasing the depth of burial. Maximum mortality was observed for 5.5 lb [2.5 kg] charges when they were buried less than 30 ft [9.2 m] into the seabed, while little or no mortality occurred with charges buried more than 30 ft down. In

experiments conducted by Hubbs and Rechnitzer (1952) with 5 lb [2.3 kg] dynamite charges, large kills of free-swimming fish were generally only recorded for charges jetted to depths of less than 30 ft but, in two experiments, fish were killed by charges at 45 [13.7] and 65 ft [19.8 m]. A 2.5 lb [1.1 kg] charge jetted to between 35 [10.7] and 40 ft [12.2 m] killed more fish than any of the other experiments, and 1.5 lb [0.7 kg] charges at depths of 30 ft also killed fish. Goertner (1981), in estimating potential fish kill associated with oil well severance explosions, calculated that a 56 lb [25.4 kg] "Comp[osition] C-4" severance charge buried 15 ft [4.6 m] in a mud bottom would have an effect equivalent to a 10 lb [4.5 kg] pentolite charge in free water. Munday *et al.* (1986) found mean predicted values for impulse strength at vector (slant) ranges of 20 to 100 m to be 5 to 6 times lower for buried charges than for mid-water charges.

The orientation of a fish to an explosion can also significantly affect the extent of injury. Sakaguchi *et al.* (1976) found that exposure of the ventral side of a fish to an explosion caused more serious effects than exposure of other sides, and damage from the caudal direction was relatively slight. The internal organs injured and the extent of these injuries also varied with the direction of the explosion. However, such effects appear to vary between species with, for example, a high proportion of common carp killed, but rock cod only slightly injured, by explosions in front of the fish.

The susceptibility of fish to explosions varies between species. Fitch and Young (1948) found that fish with a thick-walled swimbladder and a cylindrical body (eg. barracuda, kingfish, queenfish) were more resistant to explosions than laterally compressed fish with thin-walled swimbladders. Similarly, Hubbs *et al.* (1960) found the peak pressure associated with damage to fish to vary between species. Simenstad (1974) suggested that physostomous fish, in which the swimbladder is connected to the gastrointestinal tract by a small duct, would be less likely to suffer swimbladder rupture than physoclistous species, in which the swimbladder is closed, so long as the passage of gas out of the bladder was at a volumetric rate higher than the expansion of the volume of gas still within the bladder. When compared however, physostomous fish were found to be no less susceptible to explosion effects than physoclistous fish (Yelverton *et al.* 1975). Simenstad (1974) also proposed that the decompression effect on a fish would vary between species and would be primarily a function of the form of the swimbladder, the tensile strength of the swimbladder wall and the resistance of the body wall and internal organs to the expansion of the swimbladder.

Gaspin *et al.* (1976) tested the effects of explosions on twelve species of fish held in cages at depths ranging from 1.5 to 30.5 m. Of the swimbladder fish, toadfish (*Opsanus tao*) and catfish (*Ictalurus catus*) were the most resistant to damage. The thick swimbladder walls of these species was considered to reduce the incidence of rupture to that organ and, as these species were also less rigidly constructed than other species tested, the inherent flexibility of their bodies possibly cushioned the internal organs from rapid fluctuations in the size of the swimbladder. Incidence of internal haemorrhaging and bruising of the kidney was much greater in more rigidly-built fish.

The size of a fish is important and small fish are more vulnerable than larger fish (Yelverton *et al.* 1975). From calculations of fish-kill probability contours, O'Keeffe (1984) demonstrated the varying effects of explosions on fish of different weights. He also found that large fish are safer at shallower depths for a given charge size and depth of detonation, there being a greater volume of safe water near the surface than for smaller fish.

Damage caused by an explosion can also vary according to the type of explosive. Falk and Lawrence (1973) studied the effects of linear and point source explosions but their results were not directly comparable because of the different placement of the charges in the water column. Both types of charges killed fish, whereas an air gun caused no direct mortality. Subsequently, Munday *et al.* (1986) compared the effects of linear and point source charges using each type of explosive in relative amounts known to produce similar seismic records. They found values of peak pressure for linear charges to be 30 to 70% lower than for point source detonations and impulse strengths were similarly reduced by 30 to 55%.

Goertner *et al.* (1994) studied the effects of underwater explosions on fish without swimbladders. Detailed injury data were obtained from hogchokers (*Trinectes maculatus*) at distances of 20 to 80 inches (0.5 to 2 m) from a 10 pound (4.5 kg) pentolite charge. The range for 50 percent probability of immediate kill was 30 inches (0.75 m), which is a factor of 100 less than for swimbladder fish of comparable size. Their data demonstrated that these fish have an unusually high resistance to explosion effects, though the degree with which the results would carry over to other fish without swimbladders was not known.

Goertner *et al.* (1994) also reinforced the general observation that the presence of air or gas cavities is of overriding importance in causing underwater explosion injuries to fish and animals. In one experiment a number of hogchokers had air injected into the abdominal cavity to simulate the presence of a swimbladder. After the explosion, the visceral organs of these fish were completely destroyed, while the viscera of fish which had not been injected appeared undamaged.

4.2 Cause of Injury

Hubbs and Rechnitzer (1952) compared the effects of black powder charges with those of dynamite and hercomite. Dynamite, as with most explosives, detonates with a large and rapid evolution of energy, attaining its maximum intensity almost instantaneously. Once started, the disturbance is propagated through the water as a pulse of compression with a very steep shock front. In contrast, black powder burns more slowly and does not produce a shock wave with an abrupt front. The lethal threshold peak pressures measured in Hubbs and Rechnitzer's experiments varied from 40 to 70 psi [276-482 kPa or 229-234 dB re 1 μPa] for dynamite explosions but, for black powder charges, peak pressures as high as 160 psi [1100 kPa or 241 dB re 1 μPa] did not kill fish. Similarly, no dead or injured fish were recorded by divers after the detonation of 40 to 90 lb [18.2- 40.9 kg] blackpowder charges off the southern Californian coast (Fry and Cox 1953), or in experiments on the effects of blackpowder on yellow perch (Ferguson 1961). These observations indicate that it is the

very rapid change in pressure, rather than the magnitude of the peak pressure, which kills the fish. Other experiments by Hubbs and Rechnitzer demonstrated that fish could be subjected to hydrostatic pressures up to 1000 psi [6890 kPa] without apparent physical damage if the pressure was applied slowly.

Some evidence suggests that the swimbladder literally explodes when a fish is within the lethal zone of an underwater explosion (Christian 1973). Post mortems have shown that ruptured swimbladders have the edges of holes turned outwards and debris from broken blood vessels blown into the abdominal cavity (Chesapeake Biological Laboratory 1948, Hubbs and Rechnitzer 1952). External symptoms consistent with a sudden overextension of the swimbladder have included the disappearance of a small patch of scales from each side of the fish in the vicinity of the swimbladder, evisceration of the fish through the mouth or anus, and distention of the abdomen (Coker and Hollis 1950, Hubbs and Rechnitzer 1952, Tyler 1960, Christian 1973). Hubbs and Rechnitzer (1952) and Christian (1973) concluded that these injuries would more likely be inflicted by negative pressure pulses, rather than compression forces, and that such pulses would be formed when the compression wave was reflected back into the water from the air-water interface. Hubbs and Rechnitzer (1952) also proposed that this rarefaction wave would account for the greater mortality of fish near the water surface. They considered fish to be particularly susceptible to suddenly applied negative pressures and, to support this proposition, they cite the work of Hogan, who found that a negative pressure of 25 inHg [85 kPa] applied for a period of 15 seconds killed freshwater swimbladder fish, and some of their own work in which marine swimbladder fish were quickly killed by negative pressures of between 20 [68] and 30 inHg [102 kPa]. Other studies have found pressure reductions of from 14 [96] to 50 psi [345 kPa] to be lethal to physostomous fish, and a 60% reduction in relative pressure has been suggested as sufficient to rupture the swimbladder wall of a physoclistous fish (Jones 1951, 1952, Simenstad 1974). Simenstad (1974) stressed that threshold negative pressures should be considered relative to the ambient pressures in the water column. For, while the percentage volume expansion of the swimbladder gas decreases with depth and the bladder at depth is more tolerant of expansion during decompression, the threshold underpressure value triggering cavitation increases with depth and the fish is subjected to a mechanically more intense underpressure stress than in a shallower situation.

Gaspin *et al.* (1976) found that for menhaden (*Brevoortia tyrannus*), herring (*Alosa aestivalis*) and killifish (*Fundulus majalis*), the swimbladders were most frequently burst along the lateral edges of the ventral surfaces. They observed that dorsal to this area, the swimbladder wall is pressed firmly against the rib cage while ventrally the bladder shape is less rigidly maintained by contact with the viscera. The additional stress that the bladder encounters at the interface of these two different types of support was considered to help explain the high incidence of rupture in this area.

Negative pressures have also been thought to potentially cause death or injury through the formation of bubbles in the body fluids and particularly by the liberation of dissolved gases suddenly enough and in sufficient quantity to rupture the walls of unprotected blood vessels (Hubbs and Rechnitzer 1952). Simenstad (1974) considered that bulk cavitation of a fish's body fluids was a potential mechanism of physiological damage. Two mechanisms

were proposed: the accumulation of gas bubbles, especially nitrogen, in the vascular system of the organism, resulting in embolism, and the expansion of the gas bubbles to the point of inflicting physiological harm upon the blood vessels and organs. The latter process would be immediately fatal if rupturing occurred in the circulatory system, gill membranes or certain parts of the central nervous system but, in addition, sublethal damage to the peripheral nervous system or the gas exchange system for the swimbladder would increase the possibility of indirect mortality through predation.

In their study of the effects on underwater explosions on fish without swimbladders, Goertner *et al.* (1994) concluded that immediate death, in both hogchokers (*Trinectes maculatus*) and summer flounder (*Paralichthys dentatus*), appeared to be due to loss of blood resulting from haemorrhaging in the gills. These injuries were attributed to the violent radial oscillation of gas microbubbles (< 0.1 mm in diameter) present in the tissues. A second possible damage mechanism was haemorrhaging within the cranium caused by differential motion of otoliths. Impairment of swimming was observed at greater ranges from the explosion than the gill haemorrhaging, but this did not relate to observed haemorrhaging in the cranium. It was thought to be possibly due to undetected injuries to the brain and/or the nervous system.

4.3 Prediction of Lethal Ranges

Initial models for predicting the range of fish kill around an explosion assumed that damage was directly related to the compressional wave sent out by the explosion, and therefore could be related to charge weight. Lovlia *et al.* (1966) proposed a general damage rule in which lethal range was considered directly proportional to the square root of the explosive charge weight (Lavergne 1970). The relationship between lethal range (R_L m) and charge weight (W kg) was given as:

$$R_L = K\,W^{1/2}$$

The coefficient K depended upon the species of fish and varied from 12 to 54.

An alternate method for predicting fish kill, cited by Christian (1973), related lethality to the maximum pressure of the shock wave generated by the explosion (p_{max}). For most high explosive charges, p_{max} at a particular range (R) is related to the weight of the charge (W) by an equation of the form:

$$p_{max} = k\,(W^{1/3}/R)^{1.13}$$

Here, the constant k depends on the explosive material. In evaluating this relationship, Christian used the TNT peak- pressure equation given by Arons (1954), as typical variations in p_{max} for different high explosive materials were minor compared to the variability in fish kill reported from such charges. For units of pressure in psi, charge weight in lbs and range in feet, $k = 2.16 \times 10^4$ for TNT. If a particular peak pressure (P_L) is taken as lethal, then the above equation can be written as:

$$R_L = C\,W^{1/3} \text{ where}$$

$$C = 6852\,P_L^{-0.885}$$

(For pressure in kPa , charge weight in kg and range in m, $k = 5.2 \times 10^4$ and $C = 1.5 \times 10^4 P_L^{-0.885}$)

From studies with 1-10 lb [0.45-4.5 kg] dynamite charges, Hubbs and Rechnitzer (1952) suggested P_L values of 40 [280] to 70 psi [480 kPa] for the onset of lethality. Values of 70 psi for onset and 180 psi [1240 kPa] for certain lethality were estimated from studies by the Naval Ordnance Laboratory (1947).

Christian (1973) demonstrated that the ranges of fish mortality for certain weights of explosives, as calculated by the above two methods, can differ by almost an order of magnitude. Furthermore, no clear correlations were apparent between available fish kill observations and ranges predicted by these methods, as would be expected if the lethal range was a simple function of charge weight, and he proposed the need for more sophisticated explosion input. From observations that swimbladder fish are apparently more susceptible to tension than compression, and that fish near the surface are more vulnerable than fish at greater depths, Christian concluded that bulk cavitation was the most significant explosion phenomenon for predicting the most distant ranges at which fish may be killed.

Bulk cavitation is the process in which the water is "torn apart" by the surface reflected shock wave. When a shock wave hits the air-water interface, the outgoing shock wave is reflected back down into the water as a tension (negative pressure) wave which is the inverted image of the outgoing (positive) pressure wave. As a result, the pressure wave at a particular point in the water column is a combination of the outgoing compression wave and the reflected tension wave that arrives a little later. However, water cannot support much tension and when the negative pressure of the composite wave is larger than some critical pressure, the water is torn into many bubbles or cavitates. Theoretically, cavitation will not occur unless the excess negative pressure is at least as great as the hydrostatic pressure (Arons *et al.* 1949). A diagrammatic representation of the zone of bulk cavitation is shown in Figure 2. Below the zone the underpressure is less than the static pressure, which increases with depth, and the water does not cavitate. With increasing radial distance from the charge, the peak overpressure decreases and the reflected pulse arrives later to a point where the underpressure is again less than the cavitation pressure.

Gaspin and Price (1972) developed a computational method for estimating the boundaries of the bulk cavitation zone by treating the reflected charge as though it were generated by an image charge above the water surface. Using this program, Christian (1973) calculated theoretical cavitation zones for a number of charge weights and depths. He found that increasing the charge weight by an order of magnitude did not increase the size of the cavitation zone as much as expected. The maximum depth of the zone was approximately doubled but the maximum horizontal range increased by only about 20%. At the same time,

lowering a charge from 1 [0.3] to 5 ft [1.5 m] depth more than tripled the horizontal range of the cavitation zone, but did not affect its depth. Further increases in depth of detonation continued to increase the range of cavitation until a depth was reached where the pressure amplitudes at the surface were no longer large enough to trigger extensive cavitation. The range of cavitation then decreased.

There are two fish damage zones associated with an underwater explosion: the "immediate kill zone" and the "remote damage zone" (Christian 1973). The immediate kill zone is the relatively small volume of water close to the explosion in which fish will be destroyed directly by the compression wave. The remote damage zone is the much larger near-surface zone equated with the region of bulk cavitation. Whilst the dimensions of the immediate kill zone would relate directly to the size of the charge and its consequent peak overpressure, as in the models which attempted to relate fish kill directly to characteristics of the compression wave, the majority of fish would be killed in the remote damage zone.

The dimensions of the remote damage zone were defined by Christian (1973) using the extremities of the region of bulk cavitation. This generated a disc of depth V and radius H centred above the charge. The entire volume of this disc was considered hazardous, although it was considered likely that damage would be most severe near the centre of the disc and taper off towards the perimeter as cavitation became less energetic. Uncertainty was also associated with the depth of the disc as the manner in which tension waves propagate below the cavitated region was not known. However, despite these uncertainties, the model was considered useful for comparing the probable effects of different explosive charges and comparisons were made for a number of charge weights and depths. As the depth of detonation increased, H first increased rapidly, then more gradually until it passed through a broad maximum and decreased to zero at some considerable depth (eg. 600 ft [183 m] for a 1 lb [0.45 kg] charge, 2300 ft [700 m] for a 100 lb [45 kg] charge). The thickness of the layer was greatest for a shallow charge and decreased continuously as the detonation depth increased.

For shallow charge depths (< 50 ft [15 m]), Christian (1973) found that the following simple formulae could be used to approximate H and V (in feet) for charge weights up to 1000 lb [450 kg]:

For W < 100 lb [45 kg] and D < 50 ft [15 m],

$$H_{ft} = X\,W^{a}$$
$$\text{where} \quad X = 70\,D^{0.5},\ a = 0.02\,D^{0.5}$$
$$\text{and} \quad V_{ft} = 8\,W^{0.3}.$$

Damage ranges predicted by the above model were found to be in reasonably good agreement with earlier observations on the explosion effects on caged fish (Aplin 1947, Chesapeake Biological Laboratory 1948), but the limited fish kill data available was not considered to be a true test of the model. Apparent limitations of the model were its inability to predict variation in damage zone for fish of different sizes, and that it did not

take bottom reflections into account which may complicate the damage field in shallow water.

Gaspin (1975) undertook a series of experiments to test the proposed correlation between fish-kill and bulk cavitation of the water. The experiments were designed to gather high quality pressure-time records of explosion signals for comparison with observed damage to fish held in cages at fixed locations. While there was good agreement between the measured data and the cavitated region as predicted by the method of Gaspin and Price (1972), no correlation was found between cavitation and fish mortality. However, although cavitation was ruled out as the governing parameter in fish damage, negative pressure was clearly important as injuries were consistent with overexpansion of the swimbladder. Further data analyses found a strong relationship between mortality rate and the total pressure drop at the time of arrival of the surface reflection for spot (*Leiostomus xanthurus*), but there was no similar correlation for white perch (*Morone americana*).

The region of bulk cavitation was used by O'Keeffe and Young (1984) to obtain a rough estimate of the possible damage range for non-swimbladder fish, on the assumption that all fish would be susceptible to tissue damage in the cavitated region. If close enough to an explosion, all fish would also be killed by high peak pressure causing tissue damage. Damage zones for non-swimbladder fish were therefore estimated by superimposing contour plots of the cavitation zone over plots of the damage zone attributable to the incident shock wave.

Impulse was found to be the principal damage parameter in a series of experiments conducted in an artificial pond using eight different species of swimbladder fish assigned to 13 different body weight groups (Yelverton *et al.* 1975, Yelverton and Richmond 1977). From the results, a method was developed to enable the prediction of blast effects which takes into consideration fish weight (Wf g), target depth (Df m), detonation depth (D_C m) and charge weight (W_C kg). The procedure, as summarized by Wright (1982), is outlined in Table 3. Yelverton *et al.* also proposed that for fish that dwell near the bottom or next to banks, the impulse in the reflected wave should be added to that in the incident wave. Theoretically, the incident shock wave impulse was considered to double upon normal reflection but would vary with the nature of the bottom, angle of incidence and the like.

Hill (1978) tested the above model against the experimental results of several other researchers and found that the model roughly predicted the experimental results of Hubbs *et al.* (1960), Tyler (1960), Roguski and Nagata (1970) and Falk and Lawrence (1973). On this basis the Canadian Department of Fisheries and Oceans chose the lethal impulse method for the estimation of safe distances and lethal ranges for fish from underwater explosions (Wright 1982). However, they added that under certain conditions the calculated lethal ranges or safe distances should be doubled to ensure a conservative safety margin. These conditions were, firstly, if the water depth was shallow (less than five times either the detonation depth or the target depth, whichever was greater), or secondly, if the charge was detonated under thick ice. In these cases, the impulse may be increased considerably by the bottom and surface reflected shock waves respectively.

Table 3. Method for the prediction of blast effects by the impulse method (from Wright 1982). W_c is charge weight in kg, D_f and D_c target depth and detonation depth (m) respectively.

1.	Determine the impulse (I) corresponding to the degree of protection required (from Figure 3).
2.	Calculate the scaled impulse (I_{SC}), where $I_{SC} = I/W_c^{1/3}$
3.	Calculate parameter "A", where $A = (D_f \times D_c)/W_c^{2/3}$
4.	From Figure 4 find the best-fit curve to the calculated value of "A" and using the curve determine the value of the Scaled Range (R_{SC}) corresponding to I_{SC} (from 2. above)
5.	Calculate the range (R_L m), where $R_L = R_{SC}\ W_c^{1/3}$

The correlation of severe fish damage with shock wave impulse was further tested by Gaspin (1975). His data were found to support the hypothesis when the fish or charge was less than 3 m deep, but not for greater depths. Gaspin also undertook probit analysis (Finney 1952) of his data to assess possible relationships between damage level and peak pressure, impulse, energy and pressure drop but no acceptable probit fit was found. He concluded that no general damage rule for swimbladder fish could be extracted from his data.

Sakaguchi *et al.* (1976) found that energy flux density (Ef) was highly correlated with the levels of damage determined in their experiments and the lethal Ef was 300 J/m2. MacLennan (1977) calculated the "critical zone radius" R_L (m) for this E_f to be, for point source TNT explosives of weight W (kg):

$$R_L = 5.47 \times W^{0.496}$$

Hill (1978) tested this predictor against several sets of experimental data with mixed success. It did not predict the increase in lethal range with increasing depth of detonation. The model may also underestimate lethal range near shallow bottoms and under ice because of the addition of the reflected pulse, and overestimate the lethal range for fish near the surface because of the cancelling effect of the surface-reflected pulse (Wright 1982).

Goertner (1977, 1978b) developed a dynamic model to calculate the kill probability for swimbladder fish based on an approximate calculation for the extreme values of compression and extension of the swimbladder in response to the explosion pressure wave. This parameter was termed the "bladder oscillation parameter". Kill probability was calculated as an experimentally determined function of the ratio of maximum to minimum radius during the oscillatory response. For each species the effective swimbladder radius needed for the calculations was determined by correlating observed injuries with the

calculated ratio of maximum to minimum radius. The method was used to describe dissection results from 1500 fish caged at depths from 5 [1.5] to 100 ft [30.5 m] and subjected to pentolite explosions of from 1 [0.45] to 70 lb [32 kg] detonated at depths ranging from 5 [1.5] to 70 ft [21 m] (Gaspin 1975, Gaspin *et al.* 1976, Wiley *et al.* 1981). Analysis of this data set and the Lovelace Foundation data (Yelverton *et al.* 1975) showed that, if the fish and/or charge were sufficiently shallow such that no more than one cycle of bladder oscillation occurred during the positive phase of the pressure wave, damage could be directly related to impulse (Goertner 1977, 1978b). However, damage could be correlated to the bladder oscillation parameter at all depths. Strong resonance was found to occur when surface cut-off (the arrival of the rarefaction wave reflected from the water surface) coincided with maximum bladder compression and this resulted in maximum damage to the fish.

The above method and data were used to estimate the potential fish kill associated with the explosion of cylindrical charges above the water surface (Goertner 1978a), and with oil well severance explosions (Goertner 1981). In the former case, from calculations of kill probability contours and an assumed fish density, the method enabled Goertner to conclude that, on a nominal fish-killed/kg explosive basis, a typical underwater explosion is some 1000 times more hazardous to fish than the air burst geometries tested.

The complete calculation is complicated and involves the explosive pressure signature, the fish swimbladder model, and their interaction for various geometries. O'Keeffe (1984) used Goertner's model to generate contour plots of kill probability for varying parameters of charge weight (10 [4.5], 100 [45], 1000 [450] and 10000 lb [4500 kg] pentolite charges were used), depth of detonation (10 [3], 50 [15] and 200 ft [61 m]), and location and size of fish (1 oz [28 g], 1 lb [0.45 kg] and 30 lb [13.6 kg]). Each plot included contours depicting 90%, 50% and 10% probabilities of fish kill. The maximum horizontal range in feet (H_{max}) of the 10% contour was plotted against the charge weight in pounds (W) for a given fish size and the relationship found to fit the equation:

$$H_{max} = kW^a$$

where k and a are constants which vary with different fish sizes and depths of detonations (Table 4).

Although the equation can generate the maximum horizontal range of probable fish kill, it does not assess the effects on fish at different depths. For example, O'Keeffe draws attention to the apparent increase in maximum horizontal range with increase in the depth of detonation, which suggests that shallower detonations may reduce the kill. However, an analysis of the shape of the kill probability contours through the water column shows that at greater detonation depths the contour peak is closer to the water surface, thus increasing the volume of "safe" water, or water with a kill probability of less than 10%, under the contour. The two effects therefore work in opposition.

Table 4. Constants in the fish kill equation for maximum horizontal range (H_{max}) in feet and charge weight (W) in pounds (O'Keeffe 1984)

Fish Wt.		Detonation Depth	K	a
1 oz	28 g	10 ft 3.1 m	328	0.220
		50 ft 15.3 m	385	0.256
		200 ft 61.0 m	475	0.262
1 lb	0.45 kg	10 ft	174	0.264
		50 ft	235	0.275
		200 ft	272	0.299
30 lb	13.6 kg	10 ft	86	0.284
		50 ft	131	0.314
		200 ft	139	0.342

From observations on the effects of underwater blasting on fish during a construction project in Vancouver Harbour, Munday *et al.* (1986) developed a model to predict the effects of buried explosives on fish populations in shallow water. This predictive model was considered appropriate to operational conditions similar to those they monitored, but required further evaluation prior to use with different charge types, substrates and water depths.

Goertner *et al.* (1994) compared kill probability contours calculated for a non-swimbladder fish with those calculated in O'Keeffe (1984) for swimbladder fish. In all cases, the swimbladder fish were killed out to a horizontal range an order of magnitude greater than the outer limit calculated for the non-swimbladder fish. The authors therefore concluded that if precautions were taken to avoid injury to swimbladder fish in test programs, then there would be little likelihood that fish without swimbladders would be injured.

To summarize, attempts to model and predict the extent of fish kill around an underwater explosion have been based on the compressional wave emanating from the explosion, the peak pressure of the shock wave, the boundaries of the bulk cavitation zone, impulse, energy flux density and the bladder oscillation parameter. Of these, only the impulse method (under certain conditions) and the bladder oscillation model were found to correlate with results from test programs and both have been used to calculate lethal ranges and safe distances around explosions.

5. Turtles

O'Keeffe and Young (1984) observed that practically nothing is known about the effects of explosions on turtles. However, they comment that it could reasonably be assumed that a turtle's lungs and other gas-containing organs would be injured by shock waves, as is the case with mammals and birds, and their ear drums would also be sensitive. They also expected that the smaller the turtle the greater the injury from the shock wave.

In 1981, three turtles were in the vicinity of 1200 lb [545 kg] TNT charges detonated at mid-depth in 120 ft [37 m] of water during underwater shock tests off Florida. A 400 lb [182 kg] turtle 500-700 ft [153-214 m] from the charge was killed, a 200- 300 lb [91-136 kg] animal 1200 ft [366 m] from the charge suffered minor injury and another 200-300 lb [91-136 kg] animal at 2000 ft [908 m] was uninjured. From these data, and in the absence of other data, O'Keeffe and Young considered that a safe range of at least 200 ft/lb1/3 [80 m/kg1/3] was reasonable for the purpose of planning tests.

6. Birds

Tests have been undertaken which aimed to determine the effects of underwater explosions on birds on and beneath the water surface, and to develop underwater blast criteria which corresponded to safe and damaging impulse levels (Yelverton *et al.* 1973, Richmond and Jones 1974). The duck was chosen as a model and, to represent swimming and diving birds, birds were held on the surface and at 2 ft [0.6 m] depths at various ranges from 1 [0.45] and 8 lb [3.6 kg] charges.

Of the ducks tested at 2 ft depths, all those at or within a slant range of 28 ft [8.5 m] from a 1 lb charge were killed by the blast. Some survived at ranges of 31 [9.5] and 33 ft [10.1 m] and there were no deaths at 36 ft [11 m]. The impulse for 1% mortality, with 95% confidence limits, was calculated by probit analysis (Finney 1952) to be 36 (28.0 to 39.1) psi.ms [248 (193 to 269) Pa.s], and the LD50 to be 44.7 (42.8 to 47.8) psi.ms [308 (295 to 329) Pa.s]. All the ducks killed had extensive pulmonary haemorrhage, ruptured livers, and ruptured kidneys. Over half also had ruptured air sacs and eardrums, and some were observed to have suffered coronary air embolism. For birds outside the lethal zone, only the birds at 36 ft [11 m] (35.2 psi.ms [243 Pa.s]) appeared hurt. Most of these had extensive lung haemorrhage and half had kidney and liver damage. Birds exposed 83 [25] and 110 ft [34 m] from blasts were largely uninjured. Ducks exposed on the water surface were killed at slant ranges of 13 [4.0] and 14 ft [4.3 m] from 8 lb [3.6 kg] charges but not at 15 [4.6] or 21 ft [6.4 m]. The minimum impulses causing mortality were between 129 [889] and 173 psi.ms [1190 Pa.s] which is much higher than for submerged birds. This was attributed to the lungs being located above the water line. The pattern of injury for ducks on the surface was similar to those at 2 ft [0.6 m] except for the absence of kidney damage.

From the above experiments, underwater blast criteria were presented for birds on and diving beneath the water surface (Tables 5, 6). Safe ranges can be estimated from these impulse criteria using the method outlined in Table 3 for estimating lethal ranges for fish, but entering the impulse value from Table 5 at Step 2 for the required safety margin.

The Lovelace Foundation also undertook tests to determine the tolerance of birds to air shocks (Damon *et al.* 1974). The criteria for direct blast effects, based on peak pressures, were estimated to be: no injuries, 5 psi [34 kPa]; injuries, 10 psi [69 kPa]; 50% mortality, 20 psi [138 kPa]. In the case of an underwater explosion, a 20 psi [138 kPa] shock wave above the water surface is considered highly unlikely (O'Keeffe and Young 1984).

Table 5. Underwater-blast criteria for birds on the water surface (Yelverton et al. 1973, Richmond and Jones 1974).

Impulse psi.ms [Pa.s]	Criteria
130 -150 [896 - 1030]	50% mortality. Survivors seriously injured and might not survive on their own.
100 - 120 [690 - 827]	Mortality threshold (LD_1). Most survive; moderate blast injuries and should survive on their own.
40 - 60 [276 - 413]	Slight blast injuries.
30 [207]	Safe level.

Table 6. Underwater-blast criteria for birds diving beneath the water surface (Yelverton et al. 1973, Richmond and Jones 1974).

Impulse psi.ms [Pa.s]	Criteria
45 [310]	50% mortality. Survivors seriously injured and might not survive on their own.
36 [248]	Mortality threshold (LD_1). Most survivors; moderate blast injuries and should survive on their own.
20 [138]	No mortality. Slight blast injuries and a low probability of eardrum rupture.
10 [69]	Low probability of trivial lung injuries and no eardrum rupture.
6 [41]	Safe level. No injuries.

7. Sea Mammals

Some incidental observations have been made on the effects of underwater explosions on marine mammals. Californian sea lions (*Zalophus californianus*) have been reported killed by black powder explosions during seismic studies (Fitch and Young 1948), and sea otters (*Enhydra lutris*) were killed or injured by pressures of 300 and 100 psi [2070 and 690 kPa] respectively from the subterranean detonation of a thermonuclear device (Wright 1971). A 25 lb [11 kg] dynamite charge killed fur seals (*Callorhinus alascanus*) at a range of 23 m (Hanson 1954).

Although no experimental studies have been undertaken on the effects of underwater explosions on marine mammals, studies have been carried out on far-field immersion-blast effects in sheep, dogs and monkeys, and the results used to formulate underwater- blast criteria for aquatic and marine diving mammals (Yelverton *et al.* 1973, Richmond and Jones 1974). Tests involved the immersion of animals at depths of 1, 2 and 8 ft [0.3, 0.6 and 2.4 m] at varying distances from 0.5 to 8 lb [0.2-3.6 kg] explosions.

Most injuries were confined to the lungs and gastrointestinal tract. For animals at 1 ft [0.3 m] depths subjected to a 1 lb [0.45 kg] explosion, slight lung haemorrhaging occurred at a range of 26 ft [7.9 m] but at greater ranges no lung lesions were detected. Severe contusions

of the gastrointestinal tract extended out to 35 to 40 ft [10.7-12.2 m] and a single contusion occurred in one sheep at 78 ft [23.8 m]. Eardrum rupture occurred at ranges of up to 45 ft [13.7 m].

The above observations were related to impulse and slant range from the explosions, and underwater blast criteria formulated. These criteria are listed in Table 7 and apply to sublethal conditions. The criteria can be used to estimate safe ranges for mammals from explosions of differing sizes and depths of burst by using the method outlined in Table 3. The Canadian Department of Fisheries and Oceans selected this method for determining safe distances from underwater explosions for marine mammals (Wright 1982).

Table 7. Underwater-blast criteria for mammals diving beneath the water surface (Yelverton et al. 1973, Richmond and Jones 1974).

Impulse psi.ms [Pa.s]	Criteria
40 [276]	No mortality. High incidence of moderately severe blast injuries including eardrum rupture. Animals should recover on their own.
20 [138]	High incidence of slight blast injuries including ear drum rupture. Animals would recover on their own.
10 [69]	Low incidence of trivial blast injuries. No eardrum rupture.
5 [34]	Safe level. No injuries.

Hill (1978) undertook a review of the physiology of marine mammals and concluded that they were probably less vulnerable to gross physical damage from underwater shock waves than land mammals of comparable size. This was primarily due to physiological adaptations to pressure changes met while diving and secondarily to the increased thickness of the body wall.

Goertner (1982) attempted to determine the region of injury to sea mammals such as whales, porpoises and manatees. The Lovelace Foundation results (Richmond *et al.* 1973, Yelverton *et al.* 1973) were used as a starting point and scaled using plausible physical models to large sea mammals and to different charge sizes and explosion geometries.

Two mechanisms are considered primarily responsible for injuries to submerged mammals: lung haemorrhaging and oscillations of small gas bubbles in the gastrointestinal tract.

Goertner modelled these mechanisms independently, then computed two injury regions: one by the lung injury mechanism, the other by the intestinal injury mechanism. The outer boundary of these two regions was taken as the contour for incurring slight injury to the mammal. Sample computations and injury contours were presented for whales and porpoise subjected to 1,200, 10,000 and 40,000 lb [545, 4540 and 18200 kg] charges, and manatees subjected to 12 lb [5.4 kg] charges. The maximal horizontal extent of injury contours generated for the sample geometries are presented in Table 8.

Table 8. Maximum horizontal extent of slight injury to marine mammals (Goertner 1982).

Charge Weight lb [kg]	Depth of Burst ft [m]	Predicted Horizontal Range ft [m]			
		Whales		Porpoises	
		55 ft [16.8 m]	20 ft [6.1 m]	Adult	Calves
1200 [545]	125 [38]	900 [275]	1800 [549]	2700 [824]	3800 [1160]
10,000 [4540]	200 [61]	2500 [763]	4400 [1340]	5800 [1770]	8000 [2440]
	1312 [400]	3300 [1000]	6500 [1980]		
	4265 [1300]	500 [153]	7200 [2200]		
40,000 [18,200]	200 [61]	4200 [1280]	6600 [2010]	8500 [2590]	11,500 [3510]
			Manatees		
			Adult	Calves	
12 [5.5]	5 [1.5]		130 [40]	280 [85]	
	40 [12]		220 [67]	450 [137]	

An important feature of Goertner's results is the increase in the injury range for animals of decreasing size. Thus, the smaller a whale the greater the potential injury zone, and the greater susceptibility of calves to explosion effects. To put this on a more quantitative basis,

O'Keeffe and Young (1984) computed injury contours for a wide range of animal weights at the same explosion geometry. A correlation was found between the maximum range, H_{max}, and M, the weight of of the animal. For a 10,000 lb [4540 kg] charge detonated at 200 ft [61 m], the relationship was, for H_{max} in feet and M in kilograms,

$$H_{max} = -1466 \log M + 9064.$$

O'Keeffe and Young added a final word of caution. They advised that, in view of the many uncertainties in calculations, it was advisable to multiply H_{max} by at least a factor of two to provide an adequate safety margin.

8. Humans

The Lovelace Foundation experiments with animal targets (Richmond *et al.* 1973, Yelverton *et al.* 1973), which were used to predict safe ranges from underwater explosions for marine mammals, were primarily aimed at establishing safe ranges for swimmers. The injuries to test animals were related to the parameters of the explosion pressure wave and general rules developed for safe swimmer standoff. The damage level or injury was found to correlate with shock wave impulse and a safe level for human swimmers was established as 2 psi.ms [14 Pa.s].

Gaspin (1983) calculated safe swimmer standoffs for conditions of interest to personnel involved in operations such as mine clearance and underwater demolition. In addition to shock wave impulse, Gaspin also assumed involvement of peak overpressure, and a peak pressure level of 100 psi [690 kPa or 237 dB re 1 μPa] was adopted as a safe upper limit for swimmers.

From the above studies, O'Keeffe and Young (1984) determined the criteria for safety for an unprotected swimmer to be:

i. the impulse in the shock wave and its bottom reflection together is less than or equal to 2 psi.ms [14 Pa.s], and
ii. the peak overpressure is less than or equal to 100 psi [690 kPa or 237 dB re 1 μPa].

From these criteria, safe ranges were determined for TNT charge weights of 25 to 2000 lb [11-908 kg], water depths of 30 to 300 ft [9.2-92 m], and the swimmer at depths of 1 ft [0.3 m] (a swimmer at the surface) to the bottom. A selection of safe standoff ranges are presented in Table 9. Safe ranges are extremely sensitive to swimmer depth and relatively insensitive to charge weight. Thus, for a 100 lb [45 kg] charge detonated on the bottom in 30 ft [9.2 m] of water, the safe ranges for swimmers at 1 and 25 ft [0.3 and 7.6 m] depths are 250 and 1200 yd [230 and 1100 m] respectively. For a 1000 lb [450 kg] charge the corresponding safe ranges are 400 and 1700 yd [370 and 1550 m]. Increasing the charge weight by a factor of 10 increased the safe range by less than a factor of 2, whereas an increase in swimmer depth from 1 to 25 ft increased the safe standoff range by a factor of 4. On this basis, O'Keeffe and

Young considered the first safety rule for underwater explosions to be: shallower is safer, which applies to shallow charges as well as shallow swimmers.

Table 9. Safe swimmer standoffs from bottom explosions (O'Keeffe and Young 1984).

Charge Weight lb [kg]	Depth ft [m]	Safe Horizontal Range yds [m]		
		Swimmer Depth		
		1 ft [0.3 m]	25 ft [7.6 m]	75 ft [22.9 m]
25 [11.4]	30 [9.2]	200 [180]	950 [870]	
	90 [27]	350 [320]	1600 [1460]	2540 [2320]
100 [45]	30	250 [230]	1200 [1100]	
	90	400 [370]	2050 [1870]	3400 [3110]
500 [230]	30	350 [320]	1600 [1460]	
	90	650 [590]	2750 [2510]	4600 [4200]
1000 [450]	30	400 [370]	1700 [1550]	
	90	700 [640]	3100 [2830]	5250 [1600]

Studies have been undertaken in which swimmers have been exposed to impulse levels of around 2 psi.ms [14 Pa.s] (Richmond 1977). Subjects standing neck deep in a pond, 100 [30.5] to 150 ft [46 m] from where 1 lb [0.45 kg] charges were fired at a depth of 10 ft [3.1 m], were subjected to impulses ranging from 1.9 [13.1] to 4.4 psi.ms [30.3 Pa.s] and peak pressures of 73 [503] to 119 psi [820 kPa]. Sensations reported ranged from a slight ping at the lowest impulse to strong stings from the highest. Subjects were also exposed to similar impulse levels in open water, 200 [61] to 870 ft [265 m] from charges up to 194 lb [88 kg] in weight. Larger charges caused a mild thump in the lower abdomen. The wearing of a wet suit was found to reduce the sensations from what was felt by a subject in swimsuit only.

Tests were also undertaken to determine whether the sound heard from an underwater blast wave with an impulse of 2 psi.ms [14 Pa.s] would be tolerable. Subjects were tested with their ears at a depth of 1 ft [0.3 m], initially in tests using blasting caps, then with 0.5 lb [0.23 kg] charges. Distances from the charge ranged from 100 [30.5] to 25 ft [7.5 m]. None of the sound levels associated with impulses of up to 2.1 psi.ms [14.5 Pa.s] caused discomfort or tinnitus and there was never any pressure felt at or inside the ears of the subjects. Tests with dogs (Richmond *et al.* 1973) indicated that eardrums were ruptured at impulse levels of 19.2 psi.ms [132 Pa.s] and greater.

Rawlins (1988) discussed the problems and complexity of predicting safe ranges for divers from underwater explosions. Six cases in which humans were subjected to a range of explosion configurations were presented, and various parameters of the shock pulses analysed to explain the observed effects. The calculated impulse in these cases ranged from 29 [200] to 297 psi.ms [2050 Pa.s]. In open waters, for personnel submerged to a depth of 20 ft [6.1 m], and for charges not exceeding the equivalent of 20 lb [9.1 kg] TNT, lethal (R_L) and deterrent (R_D) ranges were approximated by the formulae:

$$R_L = 7\ W^{0.5} \quad \text{and} \quad R_D = 40\ W^{0.5}$$

where R_L and R_D are in ft and W in lb TNT.

However, to accurately assess the injury potential from an underwater explosion, Rawlins clearly demonstrated that explosion phenomena other than the shock pulse, including the influence of reflected waves, bubble pulses and water movement, must also be considered. For example, with large explosions at long range in shallow water, if the bottom is reflective (rock, gravel), multiple successive subsidiary pulses may impinge upon a mid-water target and give rise to resonant effects which cause disproportionately severe damage. In regard to diver protection, Rawlins reinforced the general advice that 'shallower is safer'. He further commented that although neoprene foam can reduce the peak pressure of the shock pulse, it is less effective against bubble and subsidiary pulses and also has little effect upon the impulse and energy flux values. When under compression at depth, closed cell foams can enhance explosion effects. Protection against the several components of an underwater explosion would require a rigid shell to resist the crush effect of water movement, combined with a shock absorbing material to attenuate the peak pressure of the shock wave.

9. Indirect Effects

In addition to the direct effect of an explosion on organisms in the immediate vicinity at the time of detonation, indirect effects may be caused as a consequence of direct mortality or physical disturbance from the explosion. This secondary process may involve changes in the physical and/or vegetative structure of a region which may reduce an organism's chance of survival (Simenstad 1974). The possible indirect effects of explosions on benthic vegetation, which included change in redox potential of the sediment, release of toxins,

increased water turbidity and the smothering effect of redepositing sediment, have previously been mentioned (Section 2). Such effects could equally have an impact upon bottom dwelling animal communities or prevent recolonisation. Changes in the physical or vegetative habitat, the former through cratering or changes in sediment composition, can also effect changes in the structure of the marine community by varying the suitability of the habitat to particular species, selective removal of a particular food sources, or increasing the chances of predation. An example of the indirect effects on communities due to habitat change by explosions is found in the study of Porter and Porter (1977) who found the quantity of demersal plankton rising from dynamited coral rubble to be less than from other substrate types such as branching coral, and comparable to plankton production from sand.

Many of these effects are difficult to quantify and would vary with the characteristics of a particular community. However, cratering is one effect which can be predicted. O'Keeffe and Young (1984) present the following equations which may be used for calculating crater radii for bottom explosions:

$$R_c = 3.87\, W^{1/3} (d/W^{1/3})^{0.35} \qquad \text{when } 0.08 < d/W^{1/3} \leq 0.2$$

$$R_c = 2.20\, W^{1/3} \qquad \text{when } 0.2 < d/W^{1/3} \leq 1.0$$

$$R_c = 2.20\, W^{1/3} (d/W^{1/3})^{0.30} \qquad \text{when } 1.0 < d/W^{1/3} \leq 4.0$$

$$R_c = 14.5\, W^{1/3}/Z^{1/3} \qquad \text{when } d/W^{1/3} > 4.0$$

where: R_c = crater radius in feet
d = depth of explosion (on bottom) in feet
W = charge weight in pounds, and
Z = hydrostatic pressure at the depth of the explosion (d + 33) in feet.

No consistent differences are evident between the average radii of craters in sand, clay or mixtures of these sediment types (O'Keeffe and Young 1984). However, crater depths do vary with sediment type. O'Keeffe and Young (1984) proposed that, as a first approximation, the bottom is usually disturbed over twice the diameter of the crater. Crater effects are temporary on sand or mud bottoms, but a crater in clay may persist for a period of years.

The size and persistence of the suspended sediment is less easily predicted. The amount of bottom material dislodged should be equal to the crater volume but, as large particles would settle almost immediately, this volume gives only an upper limit to the amount of material which may remain suspended (O'Keeffe and Young 1984). In general, sediment particles greater than 1 mm in diameter would settle too rapidly to form a persistent cloud and the cohesive strength of clay results in clay clumps also settling rapidly. Turbidity clouds are therefore most likely over silt or where the percentage of silt and clay exceeds fifty percent (Athearn 1968).

If an explosion takes place on or near a sloping bottom a turbidity current could be initiated (O'Keeffe and Young 1984). Such a current is formed by a suspension of sedimentary particles that flows along a seabed because the bulk density of a mixture exceeds that of clear seawater. The current moves downslope and fans out for a considerable distance. Sand and silt are gradually deposited on the bottom as the current slows and stops. Mud slides and slumps can also occur on sloping bottoms.

10. Conclusions

Two damage zones are associated with an underwater explosion: an immediate kill zone of relatively limited extent, and a much more extensive remote damage zone. Within the immediate kill zone all organisms are susceptible to damage through disruption of their body tissues by the compression wave from the explosion. However, damage in the remote damage zone is considered to be caused by negative pressure pulses, generated when the compression wave is reflected from the air-water interface. The negative pulses act on gas inclusions within the organism or cause gas embolism within tissues. Typical injuries induced by this process include lung haemorrhaging and contusions of the gastrointestinal tract in mammals and birds, and the rupture of swimbladders in fish.

While invertebrates and fish without swimbladders have been found quite resistant to underwater explosions, swimbladder fish are killed over a considerable distance. A number of models have been developed in attempts to predict the lethal range of explosions of different charge weights and depths of burst. The most successful of these are the "Impulse Method" (Yelverton *et al.* 1975) and the "Bladder Oscillation Method" (Goertner 1978b). The Impulse Method can also be used for the estimation of safe ranges for birds and mammals. The number of organisms killed or injured by a particular explosion will, however, depend on the size of populations present within the damage zones at the time of the blast. This can only be predicted from detailed knowledge of the communities present in that region.

In addition to the direct effects of an underwater explosion on marine life, indirect effects can also affect marine communities. Such effects include changes to the physical or vegetative structure of a region, decreased light penetration due to increased water turbidity, and smothering effects as suspended sediment resettles. Physical changes can include persistent cratering, changes in the redox potential of sediments making them unfit for biological recolonisation and alteration of sediment composition.

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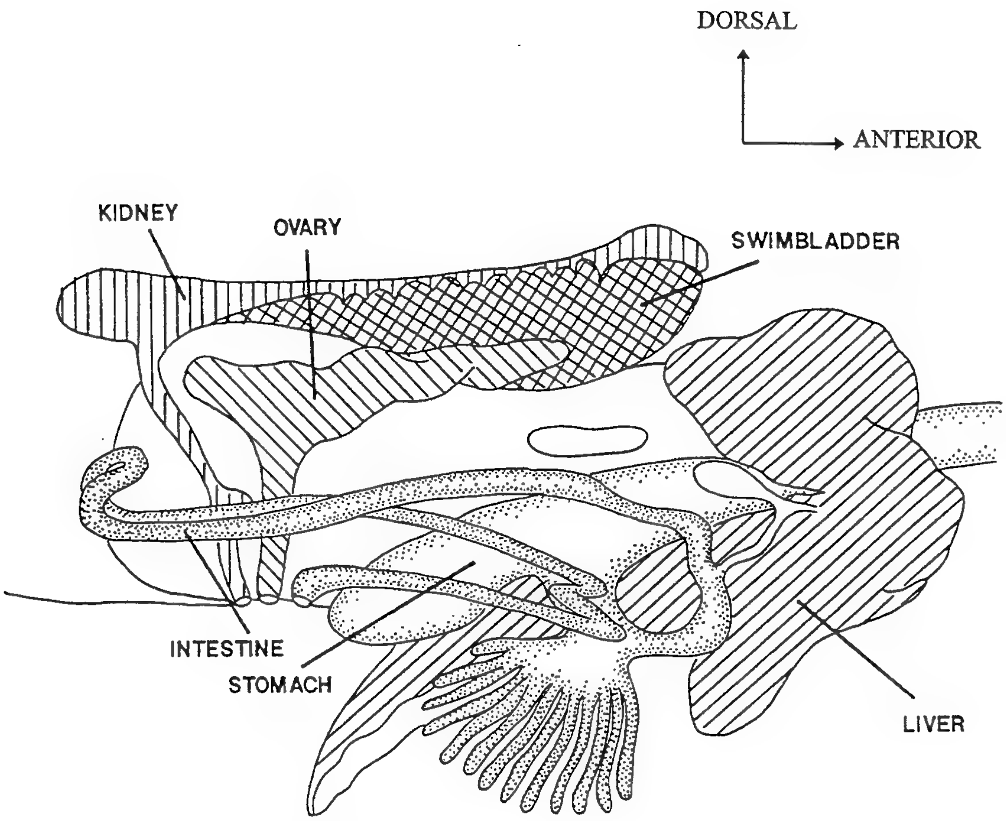

Figure 1. Dissection of organs from the abdominal cavity of a fish showing the position of the swimbladder (after de Beer 1951).

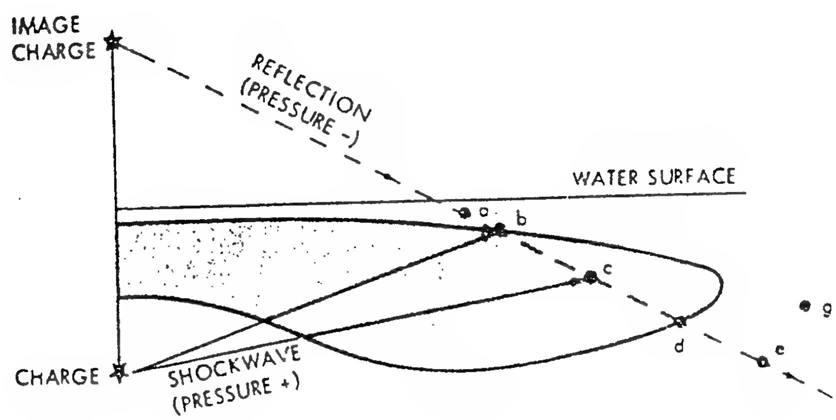

Figure 2. Diagrammatic representation of the zone of bulk cavitation (Christian 1973).

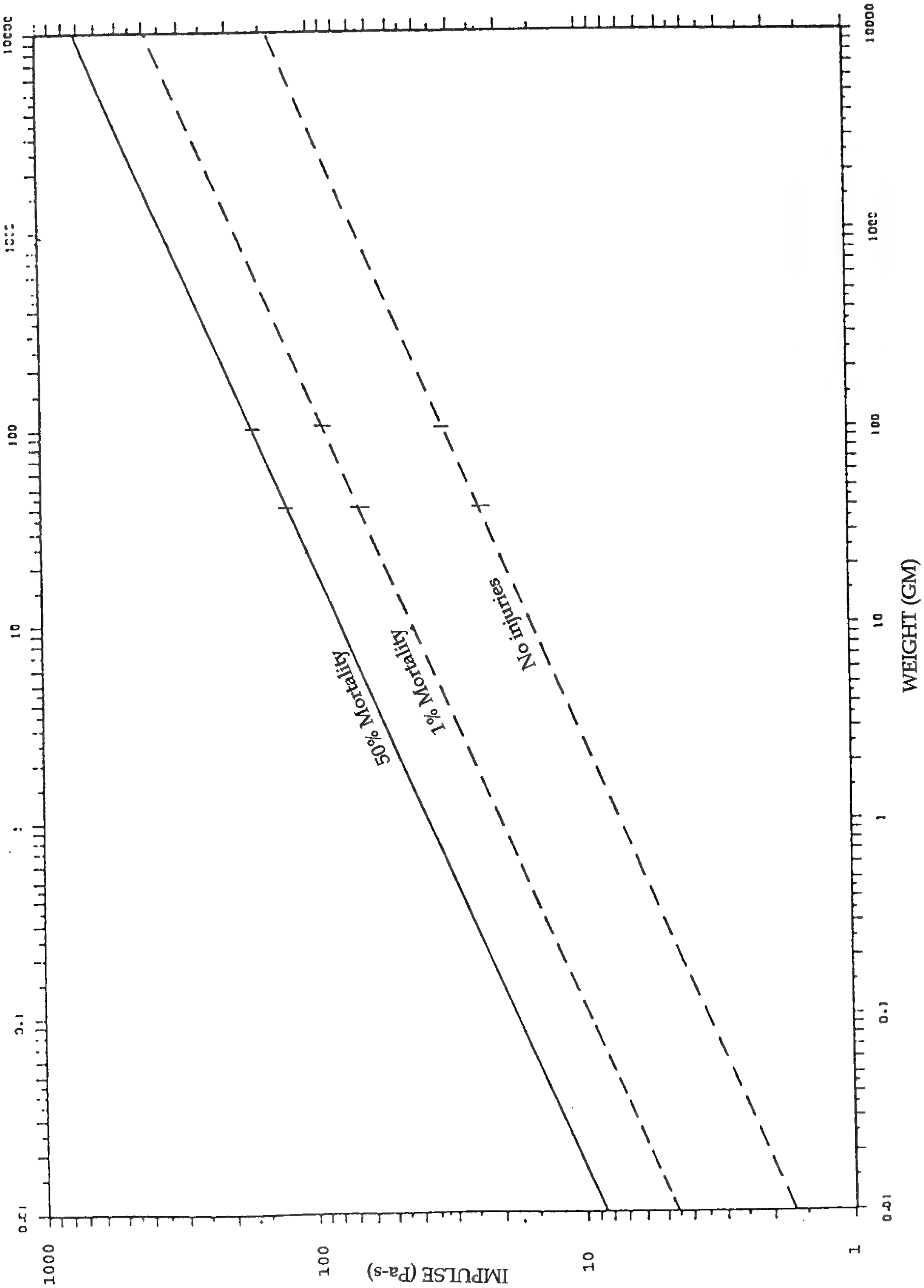

Figure 3. Lethal impulse vs. weight for fish (Wright 1982; after Yelverton et al. 1975).

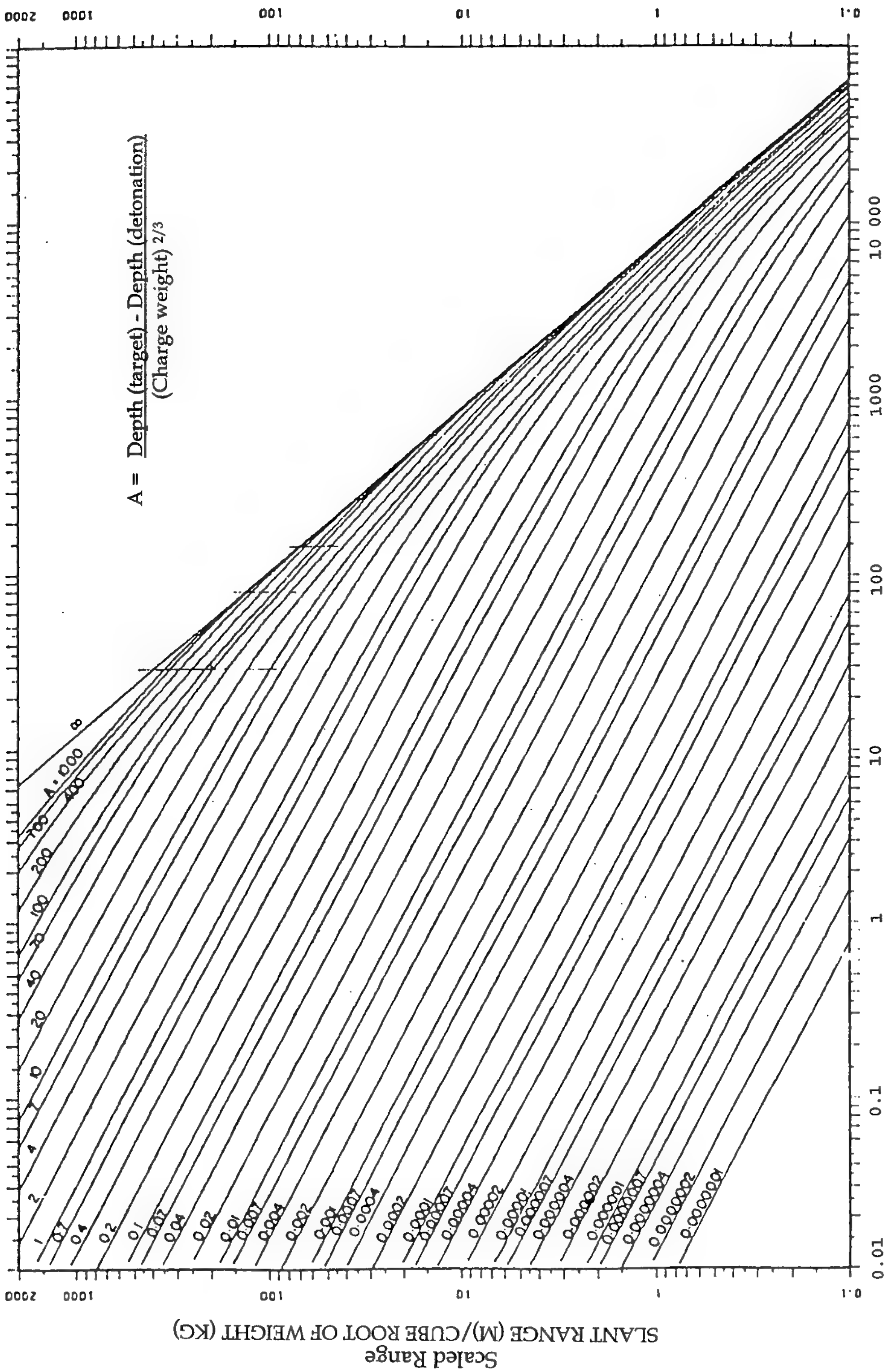

Figure 4. Curves for calculating lethal range from impulse (Wright 1982; after Yelverton 1975).

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Available literature on the effects of underwater explosions on life in the sea is reviewed. Reported effects on marine plants, invertebrates, fishes, turtles, birds, sea mammals and humans, from both experimental and field observations, are presented, as are theories on the damage process and models developed to predict lethal and safe ranges around explosions of varying configurations.